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(71) Applicant *(for all designated States except US)*: **MICMA ENGINEERING LTD.** [IL/IL]; Rotem Industrial Park, 86800 M.P. Arava (IL).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: **REZNIK, Michael** [IL/IL]; c/o Micma Engineering Ltd., Rotem Industrial Park, 86800 M.P. Arava (IL).

(74) Agents: **LUZZATTO, Kfir** et al.; Luzzatto & Luzzatto, P.O. Box 5352, 84152 Beer-Sheva (IL).

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(54) Title: SILICON CAPACITIVE ACCELEROMETER

(57) **Abstract:** Microaccelerometer which comprises a movable silicon proofmass, constututed by two silicon masses and supported by metal beam means, which is constituted by two metal beams. The two metal beams are defined in a metal plate. The proofmass may be part of an intermediate component, which comprises the metal beam means and the two silicon masses. The Microaccelerometer may also comprising two exterior insulating glass plates, carrying stationary electrodes.

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SILICON CAPACITIVE ACCELEROMETER

Field of the Invention

This invention relates to accelerometers including an upper and a lower glass plate and an intermediate silicon plate, having high resolution and sensitivity and improved shock resistance.

Background of the Invention

Capacitive accelerometers, of small size, having a vibrating proofmass formed of silicon are known in the art. Thus, USP 5,205,161 discloses a miniature accelerometer comprising a pair of spaced insulating layers, a pair of electrodes disposed on said layers, a silicon proofmass, means for sustaining the proofmass between said electrodes with gaps between each electrodes and said proofmass, means for applying an AC excitation signal to said proofmass, means for detecting AC signals, coupled to said electrodes, and means responsive to the detected AC signals for applying acceleration opposing forces to said proofmass.

USP 5,095,752 discloses a capacitive semiconductor accelerometer in which the detecting arrangement is constituted by laminating three layers, including an upper glass plate, an intermediate silicon plate and a lower glass plate.

USP 5,243,861 discloses a generally similar accelerometer, which comprises a movable electrode of silicon supported by a beam so as to permit movement in two directions substantially perpendicular to its

plane, and an upper and a lower glass plate bonded to said silicon plate and each carrying a stationary electrode. In order to create leads from said stationary electrodes, three pads are disposed on the lower glass plate at the outside of the intermediate silicon plate, a first pad being electrically connected to the stationary electrode carried by the upper glass plate and the second and third pad being electrically connected to the stationary electrode carried by the lower glass pad, via two separate thin film leads.

In an accelerometer of this type, the movable electrode is a pendulum mass of silicon which is supported by a thin lever, which must in turn be firmly held in a variable position between two insulating, generally glass, plates. To achieve this structure, an intermediate silicon plate which is worked by repeated anisotropic etching to generate the movable electrode and the thin beam which supports said electrode and permits it to swing in two directions, such as upwards or downwards. The thus generated structure is not fully satisfactory, because the thin silicon beam is fragile and relatively rigid and does not provide a suitable combination of elasticity, sensitivity and dimensional repeatability, conformity and accuracy.

Operation in the small acceleration range requires a high sensitivity of the accelerometer movable element. This can be achieved by increasing the length or reducing the thickness of beams as much as possible. However, this results in noticeable reduction of the system reliability and shock resistance.

The manufacture of silicon suspensions by chemical etching represents a rather complicated process. The non-uniformity of the etching process and excessive etching in the locations of straps attachment to the mass element and to the accelerometer body, the lengthwise non-uniformity of strap thickness, the difficulties of a high-precision thickness control, the poor controllability and reproducibility of the etching processes, and a number of other reasons, make the accelerometer manufacture process rather expensive. Besides, more often than not, it is impossible to achieve the required parameters and a high accuracy of measurements. The low reproducibility of parameters in the accelerometer manufacture process requires a more complicated technology and design, calling for additional circuitry solutions and calibration, which, in turn, leads to additional expenses and increases the cost of accelerometers.

The asymmetry of configuration arising at chemical etching of silicon requires mass balancing and, as a result, makes it necessary to apply the closed-loop control solution. This complicates both the accelerometer design and the signal processing circuit. The length and thickness limitations of silicon suspensions produce a negative effect on the parameters and characteristics of silicon accelerometers.

When designing and manufacturing ultra-miniature accelerometers, bevels resulting from the anisotropy of chemical etching essentially increase accelerometer dimensions. The use of deep ion-beam etching to the production of accelerometer elements partially solves this problem, but this process is time- and cost-intensive and requires special equipment. The pre-shaping of suspensions and structural elements on

the metal plate allows to eliminate or considerably reduce the dimensions of bevels caused by the anisotropic etching of silicon, while the possibility of using thin metal plates (a few microns thick) allows to create high resolution microaccelerometers.

As a rule, silicon sensors are inexpensive and designed for mass production. They are used in cases when a high precision of measurements is not required. To manufacture high precision silicon-based accelerometers, additional costs for the elimination of the above-mentioned drawbacks are indispensable. As a result, the cost of high precision accelerometers is rather high and restricts their application and small dimensions of accelerometer sensing devices, up to 1x1x1 mm..

It is therefore a purpose of this invention to provide a capacitive microaccelerator that is free of the aforesaid drawbacks

It is another purpose of the invention to provide such an accelerometer mechanically superior to those of the prior art.

It is a further purpose of the invention to provide such an accelerometer that has higher accuracy and sensitivity than those of the prior art.

It is a still further purpose of the invention to provide such an accelerometer which comprises a silicon proofmass supported by means having high elasticity.

It is a still further purpose of the invention to provide such an accelerometer that has durability to mechanical shocks.

It is a still further purpose of the invention to provide a process for making such an accelerometer.

It is a still further purpose of the invention to provide such an accelerometer and a process for making it that are more cost-effective than those of the prior art.

It is a still further purpose of the invention to permit the manufacture of accelerometers smaller than those of the prior art.

Other purposes and advantages of the invention will appear as the description proceeds.

Summary of the Invention

The microaccelerometer of the invention comprises an a movable silicon proofmass supported by metal beam means. The silicon proofmass is preferably constituted by two silicon masses. The metal beam means is preferably constituted by two metal beams, more preferably defined in a metal plate, called hereinafter "metal lever plate". Preferably, the said proofmass is part of an intermediate component, which will be called hereinafter "a silicon-metal-silicon structure" and will be indicated by the abbreviation SMS (and could also be called "the movable inertia element"), and which comprises: a) metal beam means, preferably two metal beams defined in a central apertured, metal plate; and b) two

silicon masses, which generate the proofmass, connected on both sides to said plate and each of which carries an electrode on its surface. Preferably, the accelerometer of the invention also comprises two exterior insulating plates, called hereinafter, for descriptive and not limiting purposes, upper and lower insulating plate; and the metal beams are in fixed position with respect to the insulating plates; and preferably the accelerometer comprises two silicon plates, through which the said intermediate component is connected to the said insulating plates. The insulating plates are preferably of glass, and they will be indicated hereinafter as "glass plates", though no limitation is intended by this. Each glass plate carries a stationary electrode. The two silicon plates are connected to the metal beam means, viz. preferably to the said central, metal plate, by soldering with a low-temperature solder. The glass plates with the stationary electrodes are connected to the said silicon plates by anodic bonding. The electrodes connected to the proofmass are called "the movable electrodes" because they move together with the proofmass. In the inactive condition of the accelerometer, they are spaced from the stationary electrodes by distances of the order of 1-2 μm on each side, to form two capacitors, the capacity of which varies as the proofmass oscillates and said distances change.

The central metal plate is of predetermined thickness and is provided by etching with apertures that define two equal beams and a plate portion supported by said beams, which portion, called hereinafter "the proofmass metal plate", supports, symmetrically on both sides thereof, the two silicon masses to form a coherent proofmass. The two silicon masses are symmetric to one another with respect to the proofmass metal plate and

will be called hereinafter "proofmass halves". They are originally of one piece each with one of the silicon plates. Once said silicon plates have been connected to the metal plates, the silicon-metal-silicon structure has been provided, and fine chemical etching for releasing the movable proofmass is carried out.

The invention further comprises a preferred process for making the accelerometer hereinbefore defined, which method comprises the following steps:

a) providing a central metal plate;

b) creating in said plate, preferably by etching, the apertures defining therein two beams and a proofmass metal plate;

c) providing two silicon plates;

d) connecting the silicon plates to the metal plate by soldering;

e) separating from each silicon plate a proofmass half, preferably by fine chemical etching;

f) connecting to each proofmass half a movable electrode, preferably by gold plating the proofmass half surface by spraying and then covering it with solder;

g) providing an upper and a lower glass plate;

h) forming on each plate, preferably by deposition, a stationary electrode, pads and leads connecting the pads to the electrodes; and

i) connecting the metal plates to the silicon-metal-silicon component, preferably by anodic bonding, in such a position that the pads of each glass plate are accessible from the outside.

The order of the recited operations is not mandatory and it must be understood that they can be carried out in any suitable order.

Brief Description of the Drawings

In the drawings:

- Fig. 1 is a cross-section of an accelerometer according to an embodiment of the invention, on the plane of symmetry of the accelerometer;

- Fig. 2 is a perspective, partially exploded, view from above of the accelerometer of Fig. 1; and

- Fig. 3 is an exploded perspective view of the structural elements of the accelerometer of Figs. 1 and 2.

Detailed Description of Preferred Embodiments

Referring first of all to Fig. 1, numerals 10 and 11 indicate the upper and lower glass plate respectively. The terms "upper" and "lower" are used only for purposes of description and have no meaning except with respect to the drawings. Numeral 12 generally indicates the silicon-metal-silicon structure (SMS). Numeral 13 generally indicates the proofmass, which comprises an upper half 14, a lower half 15, both of silicon, and a proofmass metal plate 16. The metal plate is preferably manufactured from high-strength nonmagnetic alloy with a high fatigue life operating over a wide temperature range. The material acquires high elastic properties due to thermal treatment at a temperature about 480°C. The plate is made in the form of a disk 100 mm in diameter (equal to that of the silicon plate), its thickness depending on the required measurement range, for example 10 μm.

As seen in Fig. 3, plate 16 is part of a central metal plate generally indicated at 20, which is provided with a central aperture 17 and a U-shaped aperture 18, which apertures define two equal and parallel beams 21 which support the proofmass metal plate 16. Said parallel beams have a thickness from a few microns to hundreds of microns.

14 and 15 are the inertia elements, that are etched out from silicon plates 22 and 23 respectively, as seen in Fig. 3.. Silicon plate 22 is connected at the forward end to a portion 24 of metal plate 20 and at its rear end to portion 25 of the same metal plate. The terms "forward" and "rear" are used only for purposes of description and have no meaning except with respect to the drawings. Silicon plate 23 is likewise connected at its forward portion 26 to the underside of portion 24 of metal plate 20 and at its rear portion 27 to the underside of portion 25 of metal plate 20. In this way silicon plates 22 and 23, silicon proofmass halves 14 and 15, and metal plate 20, together form the aforesaid SMS.

Additionally, the accelerometer comprises upper glass plate 10 and lower glass plate 11, which carry respectively stationary electrodes 30 and 31, stationary electrode 30 being on the underside of plate 10 while stationary electrode 31 is on the upper side of glass plate 11, viz. both electrodes being in the interior of the accelerometer. The stationary electrodes are formed by deposition. Since it is necessary to be able to receive the signals from the stationary electrodes on the outside of the accelerometer, in spite of their position in its interior, stationary electrode 30 is connected by thin leads to pads 32 and stationary electrode 31 is connected by thin leads to pad 33, and the glass plates extend beyond the SMS, as clearly seen in Fig. 1, so that pads 32 and 33 are exposed and

accessible on the outside of the accelerometer. Correspondingly, the SMS carries two mobile electrodes, an upper electrode 35 and a lower electrode 36, which define capacitors with stationary electrodes 30 and 31 respectively. The capacity of said capacitors vary as the SMS vibrates, with the consequences that are well known to skilled persons. To provide a gap between the stationary and mobile electrodes, a recess of e.g. about 2 μm deep, is etched out at the inertia element location. The etching depth is chosen so that after the deposition of the electrodes the gap between them does not exceed 1 μm.

The preferred way in which the accelerometer is made is the following. The glass plates 10 and 11 are provided in a conventional way with the stationary electrodes, the leads and the pads. The apertures are formed in the metal plate 20 by chemical etching. Two silicon plates are provided, having flat upper and lower surfaces and contoured as generally shown in Fig. 3, and are provided by deposition with pads 37 and 38. Mobile electrodes 35 and 36 on the silicon surface of the inertia elements are electrically connected by conductive silicon to the metal plate. Said electrodes represent a single (common) electrode inside the sensor. The electrical contact with said electrodes is implemented through the bonding pad 37 or 38.

The metal plate and the silicon plates are mutually connected by soldering. Thereafter the proofmass halves 14 and 15 are separated from the respective silicon plates by fine chemical etching. The glass plates are bonded by anodic bonding, via the silicon plates, to the intermediate silicon-metal-silicon structure created by the above operations, in the

appropriate positioned relationship, thus completing the creation of the accelerometer.

The accelerometer of this invention is particularly intended for the operation in the small acceleration range, up to ±2 g, where the high accuracy of measurements and the sensitivity of 0.01 mg are ensured, but may be used equally well for higher acceleration ranges. It has a number of advantages as compared with the prior art accelerometers of similar design.

1. The transducer straps are formed from alloy with high elasticity properties imparted to the latter by heat pretreatment and preserved during the manufacture of the accelerometer.

2. The straps are formed on a metal plate by chemical etching prior to connecting the metal plate to silicon plates, thus providing a high degree of dimensional accuracy of the elements.

3. The thickness of metal foil is determined with a high degree of accuracy, and, consequently, that of the beams supporting the proofmass has an accuracy that is unattainable when producing them by chemical etching of silicon.

4. The use of metal alloy foil for the production of movable elements allows:

- producing proofmass supporting beams with a thickness from a few microns to hundreds of microns for the operation in any dynamic range from tens of g up to hundreds of thousands of g;

- producing such beams of many sizes and configurations with a high accuracy and obtaining the required frequency characteristics;

- producing such beams without any size limitations and ensuring at the same time a higher shock and acceleration resistance (better than 20,000 g.);

- producing accelerometers without additional damping and shock protection;

- ensuring a high linearity, low hysteresis and high durability of the accelerometer due to mechanical and heat treatment of the alloy film;

- producing ultra-miniature accelerometers with predetermined characteristics;

- producing smaller accelerometers where it is needed and using less silicon ;

-manufacturing micro electromechanical systems (MEMS) accelerometers in the low acceleration range e.g. 0.1 g full scale.

5. The accelerometer of the invention allows measuring small magnitudes of acceleration under simultaneous effect of high accelerations and impact loads.

It is to be noted that the new technology herein described can be used for other micro electromechanical systems that are not used as accelerometers.

Although embodiments of the invention have been described by way of illustration, it will be apparent that the invention can be carried out with many modifications, variations and adaptations, without departing from its spirit, or exceeding the scope of the claims.

CLAIMS

1. Microaccelerometer which comprises a movable silicon proofmass supported by metal beam means.

2. Microaccelerometer according to claim 1, wherein the silicon proofmass is constituted by two silicon masses.

3. Microaccelerometer according to claim 1, wherein the metal beam means is constituted by two metal beams.

4. Microaccelerometer according to claim 1, wherein the two metal beams are defined in a metal plate.

5. Microaccelerometer according to claim 2, wherein the proofmass is part of an intermediate component, which comprises the metal beam means and the two silicon masses.

6. Microaccelerometer according to any one of claims 1 to 5, further comprising two exterior insulating plates carrying stationary electrodes.

7. Microaccelerometer according to claim 6, wherein the insulating plates are made of glass.

8. Microaccelerometer according to claim 5, wherein the intermediate component is a silicon-metal-silicon structure comprising:

a) a central apertured, metal plate;

b) two silicon masses, connected on both sides to said plate and each of which carries an electrode on its surface; and

c) two silicon plates, through which the intermediate component is connected to two exterior insulating plates.

9. Microaccelerometer according to claim 8, wherein the metal plate is made of high-strength nonmagnetic alloy with a high fatigue life operating over a wide temperature range.

10. Microaccelerometer according to claim 8, wherein the metal plate is a disk having a diameter of about 100 μm.

11. Microaccelerometer according to claim 8, wherein the two silicon plates are connected to the central, metal plate by soldering.

12. Microaccelerometer according to claim 8, wherein the insulating plates are connected to the silicon plates by anodic bonding.

13. Microaccelerometer according to claim 8, wherein, when the microaccelerometer is inactive, the electrodes connected to the silicon masses are spaced from stationary electrodes carried by the insulating plates by distances of the order of 1-2 μm

14. Microaccelerometer according to claim 8, wherein the central metal plate is provided with apertures that define two equal beams and a plate portion supported by said beams.

15. Microaccelerometer according to claim 6, wherein the stationary electrodes carried by the insulating plates are connected to pads located on said plates in such a position as to be accessible from the outside of the accelerometer.

16. Process for making a microaccelerometer, which comprises the following steps:

a) providing a central metal plate;

b) creating in said plate apertures defining therein two beams and a proofmass metal plate;

c) providing two silicon plates;

d) connecting the silicon plates to the metal plate;

e) separating from each silicon plate a proofmass half;

f) connecting to each proofmass half a movable electrode;

g) providing an upper and lower insulating plate;

h) forming on each insulating plate a stationary electrode, pads and leads connecting the pads to the electrodes; and

i) connecting the insulating plates to the silicon plates in such a position that the pads of each insulating plate are accessible from the outside.

17. Microaccelerometer, substantially as described and illustrated.

18. Process for making a microaccelerometer, substantially as described and illustrated.

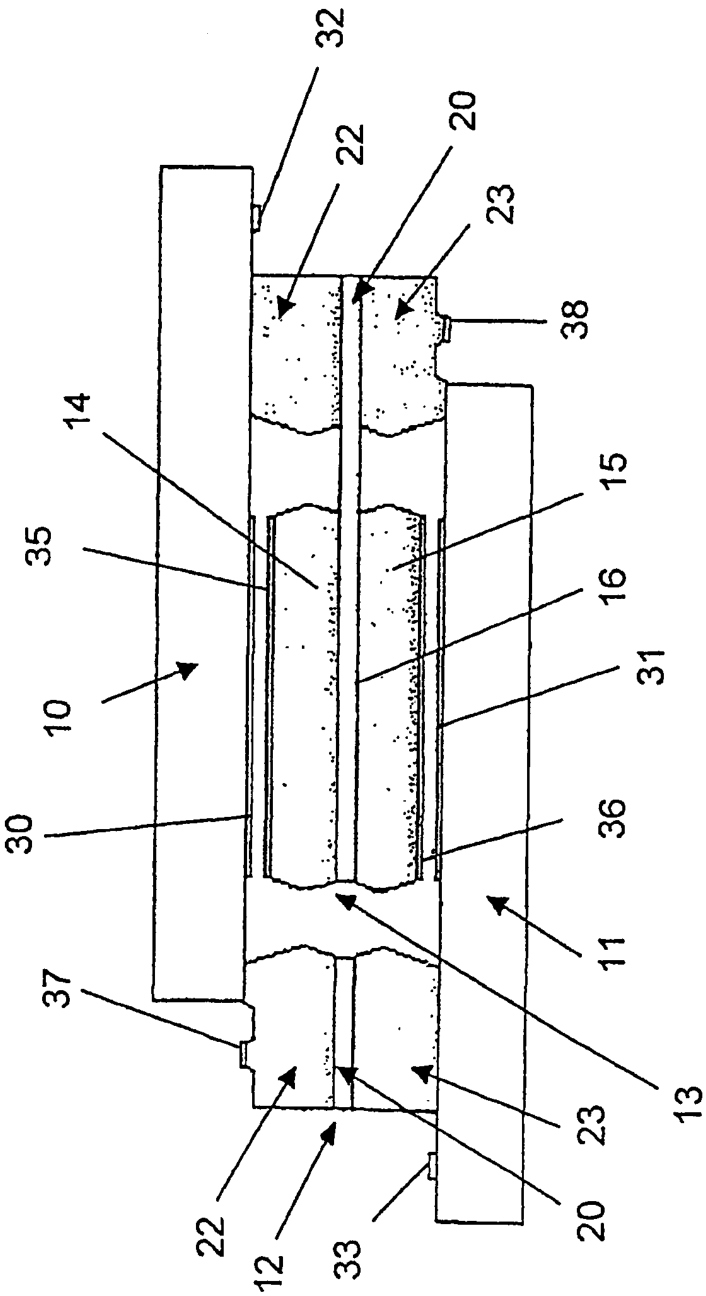

Fig. 1

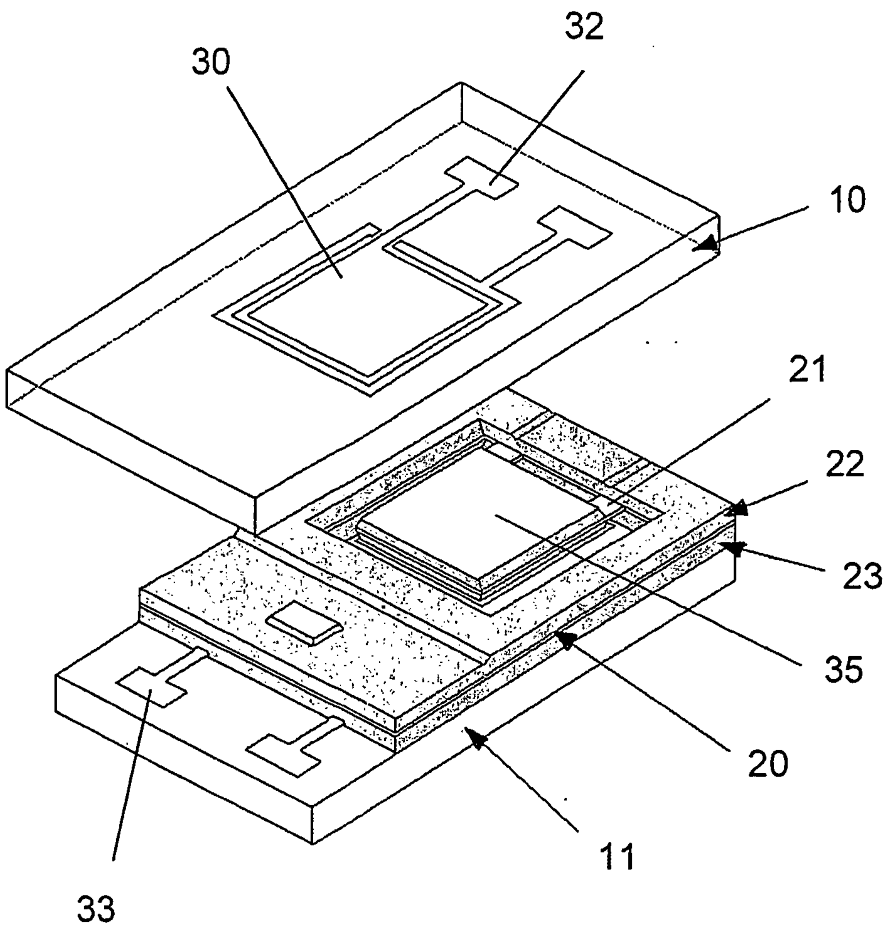

Fig. 2

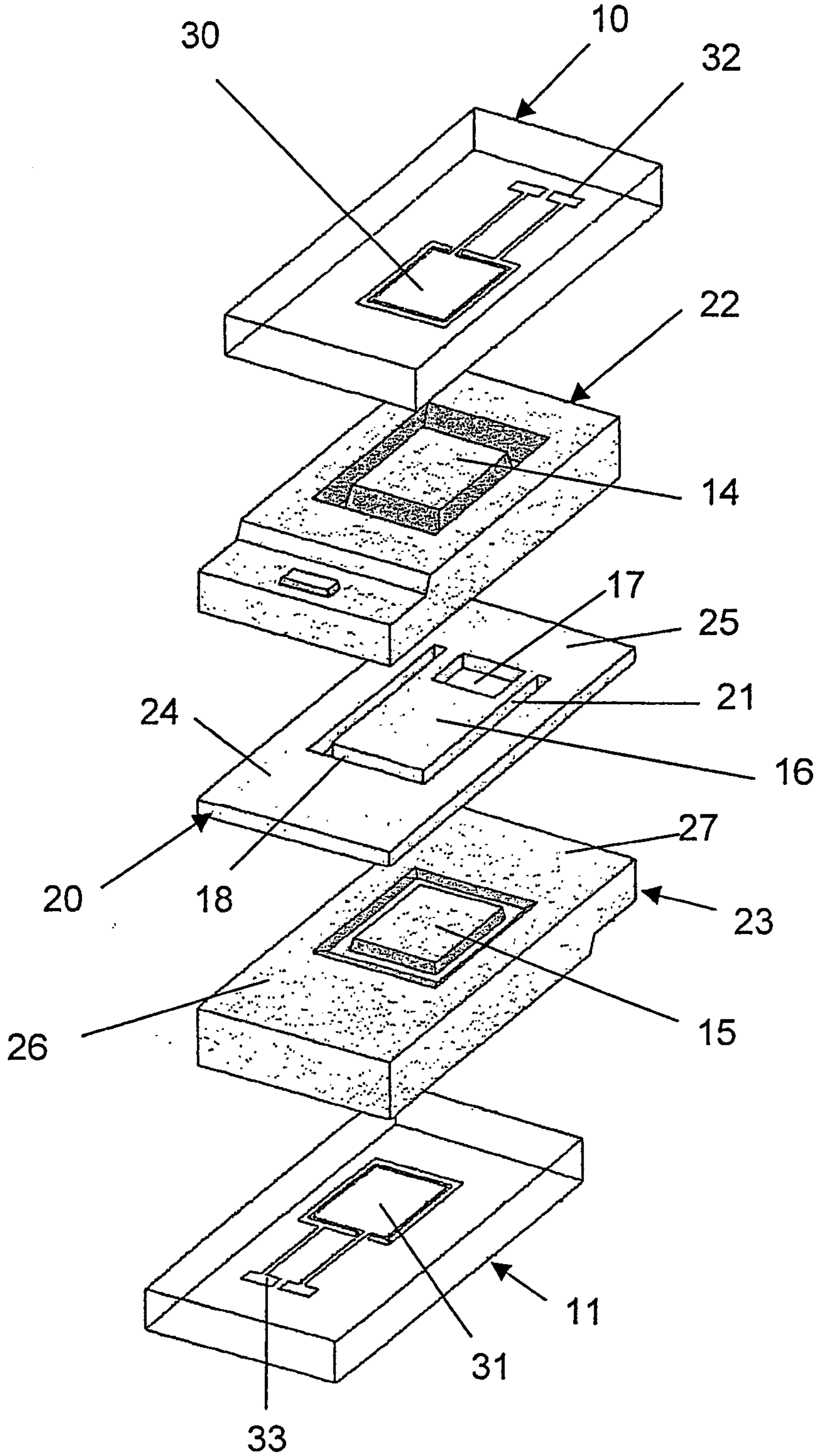

Fig. 3